LONG-TERM CONTROL MECHANISMS OF STREAM PIRACY PROCESSES IN SOUTHEAST SPAIN

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ABSTRACT

The Guadix Basin developed as an endorheic depression during the Upper Miocene–Upper Pleistocene. Its principal palaeogeographical characteristics are a large lake in the eastern sector, an axial fluvial system and two fluvial systems transverse to it in the western sector. The uplift of a central sector of the Betic Cordillera during the Upper Pleistocene affected the study area, causing northward tilting from the Internal Zone of the cordillera (Sierra Nevada and Sierra de Baza), step-faulting of the Plio-Pleistocene infill of the ancient basin (leaving more northern sectors in a lower topographical position), alteration of fluvial current profiles and displacement of the ancient Axial System to a position very close to the divide between the ancient endorheic Guadix Basin and the Guadalquivir Basin. This facilitated capture of the endorheic basin by the headward erosion of a tributary of the Guadalquivir River. The region then began to be rapidly eroded, as the new base level was now some 500 m lower than that of the ancient basin. The present drainage network is similar to that of the ancient endorheic basin as regards the location of the main streams and the distribution of drainage patterns and fluvial styles, although flow reversal is found in some stretches and a barbed drainage pattern appears locally. As a result of the inheritance of drainage from the ancient basin, fluvial superimposition is found in some stretches of the main streams. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The geomorphic characteristics of present-day fluvial systems are frequently the result of the geological evolution of the region where they are located. Analysis of the main features of a drainage pattern is therefore aided by taking into account the geological context and the factors controlling the evolution of sedimentary basins drained by present-day streams (McKenzie, 1978; Bally and Snelson, 1980; Miall, 1981, 1984; Wernicke, 1985; Coward, 1986). Also of use are the processes involved in the transformation of a region subjected to prolonged subsidence in an area of net erosion (e.g. Ziegler, 1984; Viseras and Fernández, 1992; Mather, 1993).

After a prolonged history of subsidence followed by basin inversion (formation of a deep basin in an area formerly occupied by land that produces quantities of sediments (Bates and Jackson, 1990)), a continental depression exclusively occupied by alluvial and lacustrine environments *sensu lato* can present either important changes in the position of the drainage network and fluvial styles, or simply slight alterations to the basic features and position of the network. A combination of allocyclic (external to the sedimentary systems) and autocyclic (caused by the sedimentary systems themselves) factors determines which of the two situations occurs.

The most important allocyclic factors are: climate, which can cause significant alterations in sediment supply and the base level of the fluvial systems; local geological factors, such as the structure and lithology of the basement and the materials surrounding the basin; recent tectonic movements, responsible for changes in the slope of the river channels and also alteration of the fluvial profiles through modification of the position of the region relative to base level.

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The most important autocyclic factors are changes in position of the fluvial channels, either by sudden shift mechanisms (avulsion) or by continuous lateral migration.

This paper is mainly concerned with the processes involved in the transformation of a basin from endorheic to exorheic as a result of fluvial piracy in an area of southeast Spain. The analytical method applied consisted in comparison of the drainage network occupying the region during the subsidence and post-inversion stages. We show how the differences between the two stages as regards stream location, fluvial styles and flow directions and the overall evolution of the hydrographic network provide a great deal of information on the processes controlling basin inversion and the appearance of some features, such as fluvial superimposition, detected in the present hydrographic network of the area.

Harvey (1987), Harvey and Wells (1987), Friend (1989) and Mather (1993) described other cases of recent drainage networks in Spain with reference to the palaeogeography of ancient sedimentary basins.

GEOLOGICAL SETTING OF THE ANCIENT BASIN

The northern sector of Granada province (Spain) is an intermontane region that was occupied during the Upper Miocene–Pleistocene by a sedimentary basin known as the Guadix Basin. This basin occupied a central zone of the Betic Cordillera which, together with the North African Rif, is the westernmost alpine chain in the Mediterranean area, basically caused by closure of the Tethys due to African–Eurasian plate convergence (Sanz de Galdeano, 1990). The Betic Cordillera is traditionally divided into two main zones known as the External and Internal Zones. The External Zone comprises the sedimentary cover rocks of the South Iberian continental palaeomargin that were folded and thrust in a northwesterly direction onto the Iberian foreland during the Palaeogene and Miocene (García Hernández *et al*., 1980; Banks and Warburton, 1991; Sanz de Galdeano and Vera, 1992; Geel *et al*., 1992; Martin Algarra *et al*., 1992). In contrast, the Internal Zone (or Alboran Domain (Balanyá and García Dueñas, 1988)) consists mainly of metamorphic rocks that were deformed and metamorphosed during alpine events prior to the Miocene (Puga *et al*., 1989; Lonergan and Mange-Rajetzky, 1994).

The Guadix Basin was located on the contact between these two main geodynamic domains (Figure 1) and developed as a continental basin towards the Upper Miocene (Viseras, 1991; Soria and Ruíz Bustos, 1992; Vera *et al*., 1994). The continental filling, composed of alluvial and lacustrine sediments, spans a period of some 6·5 Ma (the upper part of the Upper Miocene, Pliocene and Lower and Middle Pleistocene). The fluvial capture process analyzed here marks the moment of basin inversion and the beginning of the rapid erosion of the area. This took place during the Upper Pleistocene, sometime between 100 000 years BP (approximate age of the most recent archaeological site in the infill of the ancient basin (Botella *et al*., 1985, 1986)) and 16 300 years BP (age of the most ancient deposits dated in the present-day drainage network (Jiménez de Cisneros, 1994)).

PRE-INVERSION PALAEODRAINAGE PATTERN

The general paleogeography of the basin has been described in detail in previous papers (Fernández *et al*., 1991, 1993; Viseras, 1991; Viseras and Fernández, 1992; Vera *et al*., 1994). Here we shall only emphasize those features of the ancient drainage network that are most significant for comparison with the emplacement and geomorphological characteristics of the present-day rivers crossing the region. The geomorphic features of the ancient fluvial network described in this study were obtained from an architectural element analysis (Miall, 1985, 1988).

On the basis of sedimentological data and compositional information on the fine sediments and petrology of the clasts making up the continental sediments, a large lake (eastern sector of the basin, Figure 1) and three fluvial systems can be detected in this endorheic basin.

Plio-Pleistocene master drainage ran parallel to the main axis of the basin, for which reason we refer to it as the Axial System (Figure 1). Two other alluvial systems joined the central system transversally, one located to the north and northwest draining the reliefs of the External Zone, and the other draining the relief of the Internal Zone, located to the south. These two systems have therefore been called the External and Internal Transverse Systems (Figure 1).

The Axial System ran southwest to northeast through a gently sloping valley, developing a meandering fluvial pattern with a main channel up to 60–80 m wide and 5–6 m deep in its most distal part. This is estimated from the analysis of coarse-grained point bars developed along most of its course (Viseras, 1991; Fernández *et al*., 1991).

The Plio-Pleistocene Internal Transverse System is made up of a series of alluvial fans reaching 10–11 km in radius and deposited by a network of low-sinuosity braided channels. These were streams subjected to a high rate of lateral migration (Viseras and Fernández, 1994, 1995) as a result of the development of gravelly fingered braid bars (Bluck, 1987) along most of their course.

The External Transverse System was also made up of somewhat smaller fans (Fernández *et al*., 1993). The channels of these fans were straight (as understood by Allen (1965), Miall (1977) and Schumm (1981)), less than 4 km in length and with a low rate of lateral migration. Steeply sloping channels can be inferred by the presence of structures such as transverse clast dams (Bluck, 1987), pebble clusters (Billi, 1988) or boulder steps (Grant *et al*., 1990).

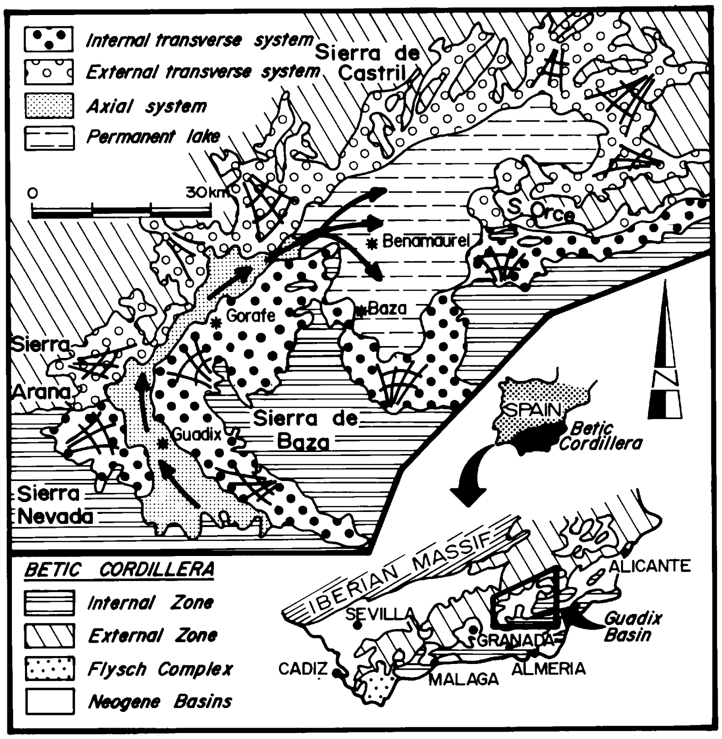

Figure 1. Pre-inversion geological setting of the study are and distribution of the major alluvial and lacustrine environments in the Guadix Basin. Note the presence of one axial and two transverse alluvial systems (External and Internal) and a large lake in the eastern section of the basin. The arrow indicate the flow direction in the Axial System.

RECENT DRAINAGE PATTERN, GEOMORPHOLOGY AND CLIMATE

The area occupied by the Plio-Pleistocene endorheic sedimentary basin (approximately 3500 km^2) is at present crossed by an exorheic fluvial network draining north towards the Guadalquivir River via the Guadiana Menor River in a zone approximately corresponding to the central part of the ancient basin (Figure 2). Downcutting through the Plio-Pleistocene continental filling and the Mesozoic and Cenozoic substratum has created a typical badlands relief (Wise *et al*., 1982).

The modern climate is semi-arid and presents intense seasonal activity, which are characteristics common to all of SE Spain during the Quaternary (Harvey, 1984, 1990; Mather, 1993). The low rainfall in this particular

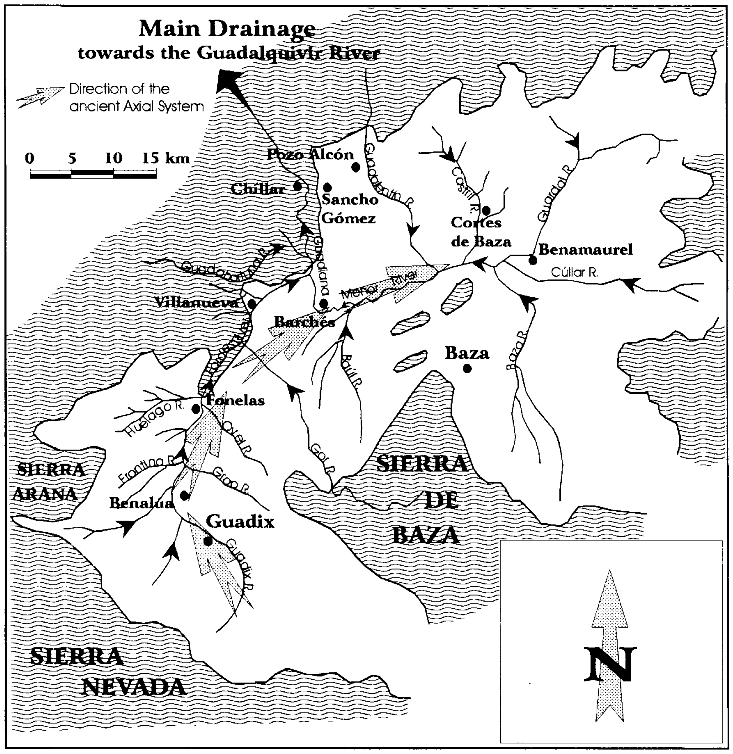

Figure 2. Recent drainage network sketched from Landsat Imagery.

area is partially due to the rain-shadow effect of Sierra Nevada. Annual rainfall in the central sector of the area ranges from 290 to 350 mm, with only 35 days of rain, on some of which rainfall exceeds 60 mm.

An eastern and a western sector can be distinguished in the present situation. The eastern sector is occupied by a centripetal drainage pattern formed by the confluence of the rivers Guadalentín, Castril, Guardal, Cúllar and Baza leading to the Guadiana Menor River, which flows ENE–WSW through the Benamaurel-Barchés reach (Figures 2 and 3).

The western sector, on the other hand, is occupied by a dendritic network with the Fardes River as trunk stream. Streams located to east and west flow into the Fardes, the most important of which are the Guadix, Huélago and Gor Rivers (Figures 2 and 4). Finally, the Fardes flows into the Barchés-Chíllar reach of the Guadiana Menor, through which main northward drainage takes place.

As shown below, both the geographic emplacement of the drainage network and the geomorphic characteristics of the streams show significant similarities between the drainage network of the sedimentary basin in the Pliocene and Lower and Middle Pleistocene (prior to basin inversion) and the present-day fluvial pattern.

Thus, due to their similarity in orientation, the Guadix River and the Fardes, from Benalúa downstream, are the modern equivalent of the ancient Axial System (Figure 2), while the Castril, Guadalentín, Huélago and Frontina Rivers correspond to the ancient External Transverse System and the Grao, Ovel, Gor and Baúl Rivers are equivalent to the Plio-Pleistocene Internal Transverse System. The ancient Axial System continued eastwards along the same position as the Guadiana Menor (Benamaurel-Barchés reach).

By also analysing the fluvial styles of the Holocene streams, we can see that the rivers draining the Sierra de Baza (recent Internal Transverse System) show braided-type patterns, with development of fingered braid bars and very high rates of lateral migration causing erosion of the Holocene terraces. The bed slope is less than 0·07. On the other hand, the rivers draining the External Zone have lower sinuosity and higher slope (0·05–0·12). They develop longitudinal bars with no clear tendency for lateral migration towards the banks, with

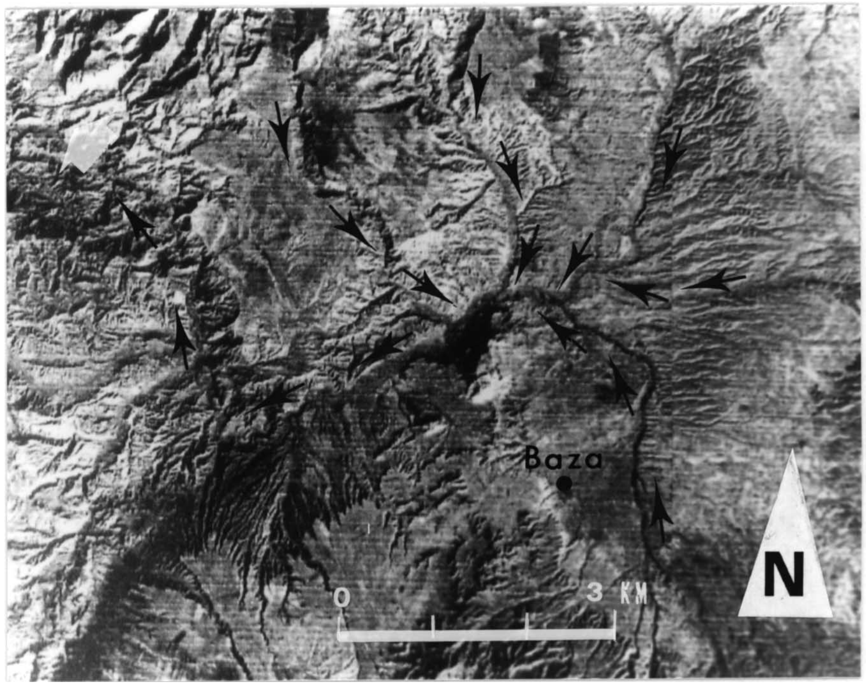

Figure 3. Landsat image showing the centripetal network in the eastern sector of the area, formerly occupied by a lake. Main northward drainage is also shown (top left corner of photograph)

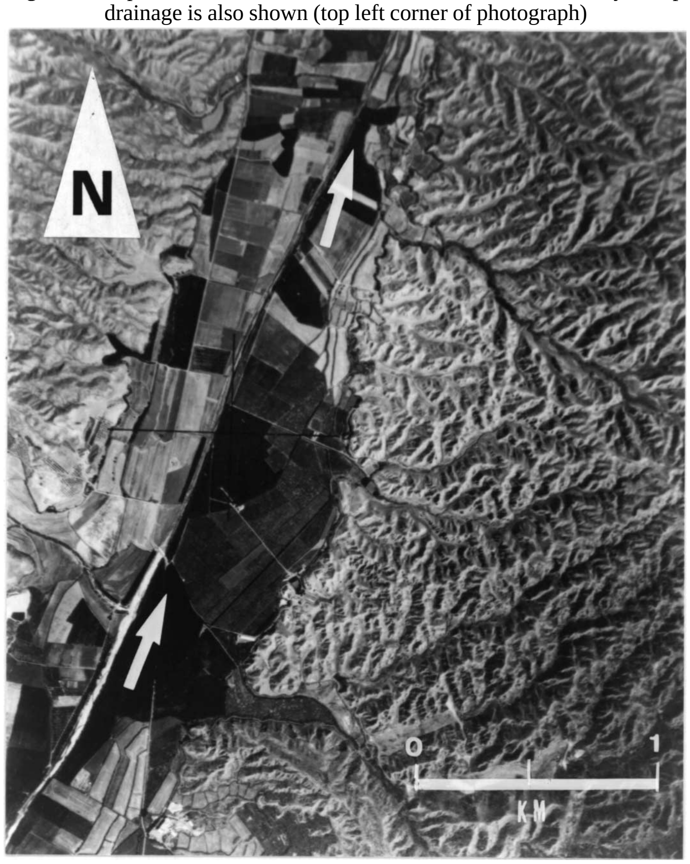

Figure 4. Dendritic drainage pattern with a trunk stream and badlands development in the western sector of the area. Agricultural activity is only possible on terraces of the trunk river (Fardes) (location: south from Fonelas)

Figure 5. Good preservation of terraces in the present-day streams of External Transverse System (location: north from Benalúa)

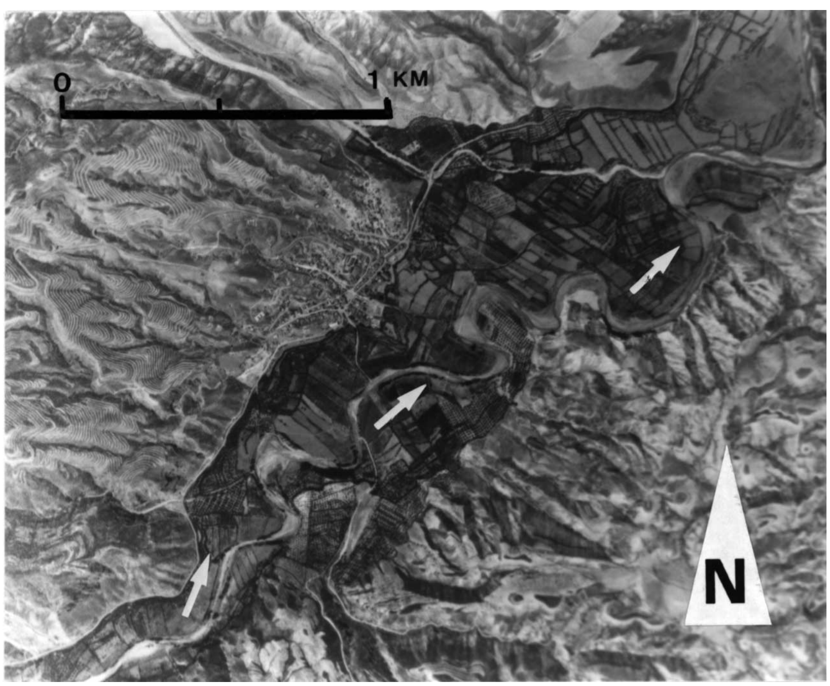

Figure 6. Fardes River meander belt near Villanueva. Arrows indicate flow direction

sedimentary structures such as transverse clast dams, boulder steps or pebble clusters. Their rate of lateral displacement is therefore lower, as shown by the better preservation of the Holocene terraces (Figure 5). To conclude this comparison of the sedimentary and geomorphic characteristics of the streams now crossing the area and those occupying the basin in the uppermost Miocene, Pliocene and Pleistocene, it should be noted that the trunk currents with a similar position to that of the ancient Axial System, i.e. the Fardes and Guadiana Menor Rivers, develop a meandering fluvial style (Figure 6), with coarse-grained point bars much larger than the longitudinal and bank-attached bars of the transverse streams.

EVIDENCE OF FLUVIAL SUPERIMPOSITION AND STREAM PIRACY

Despite the similarities mentioned above, there are a number of anomalous features regarding the geographical location and geomorphological characteristics of the hydrographic network that suggest superimposition of the ancient drainage network.

Evidence of superimposition can be found in the Fardes River (Fonelas-Villanueva reach) and the Guadiana Menor (Barchés-Chíllar reach), which present high-sinuosity patterns on passing over the basement rocks of the ancient sedimentary basin. When the fluvial network began to become entrenched, these rivers maintained their meandering style, given the easily erodible nature of the gravels and poorly lithified sands filling the basin. Signs of superimposition occur when erosion reached the basement, since the meandering pattern was maintained without being apparently affected by the structure of harder lithology of the rocks forming the substratum (Figure 7A and B).

In view of the foregoing, there seems to be close coincidence between the geomorphic styles of the present

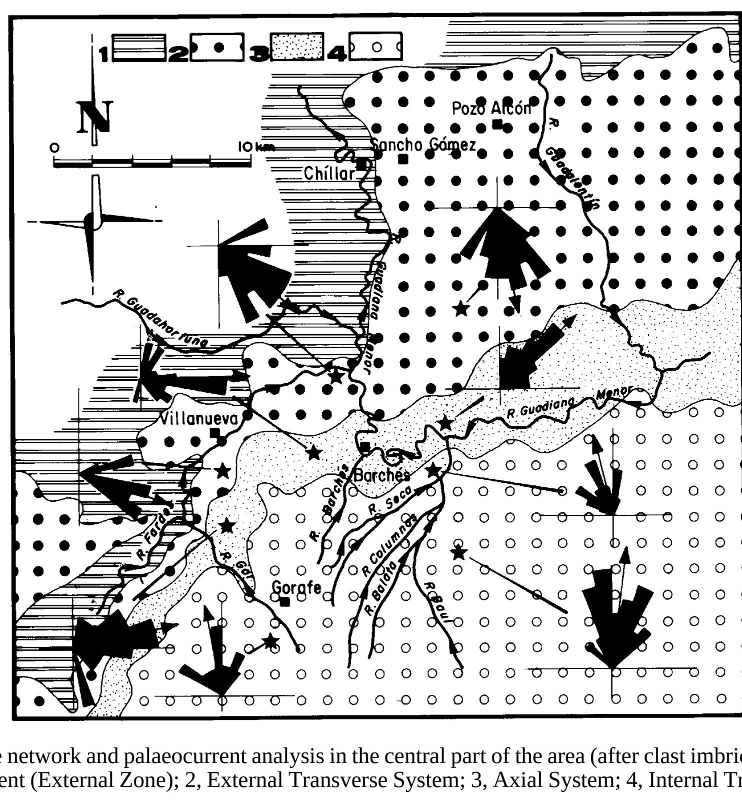

Figure 8. Recent drainage network and palaeocurrent analysis in the central part of the area (after clast imbrications, flutes and grooves). Key: 1, Basement (External Zone); 2, External Transverse System; 3, Axial System; 4, Internal Transverse System

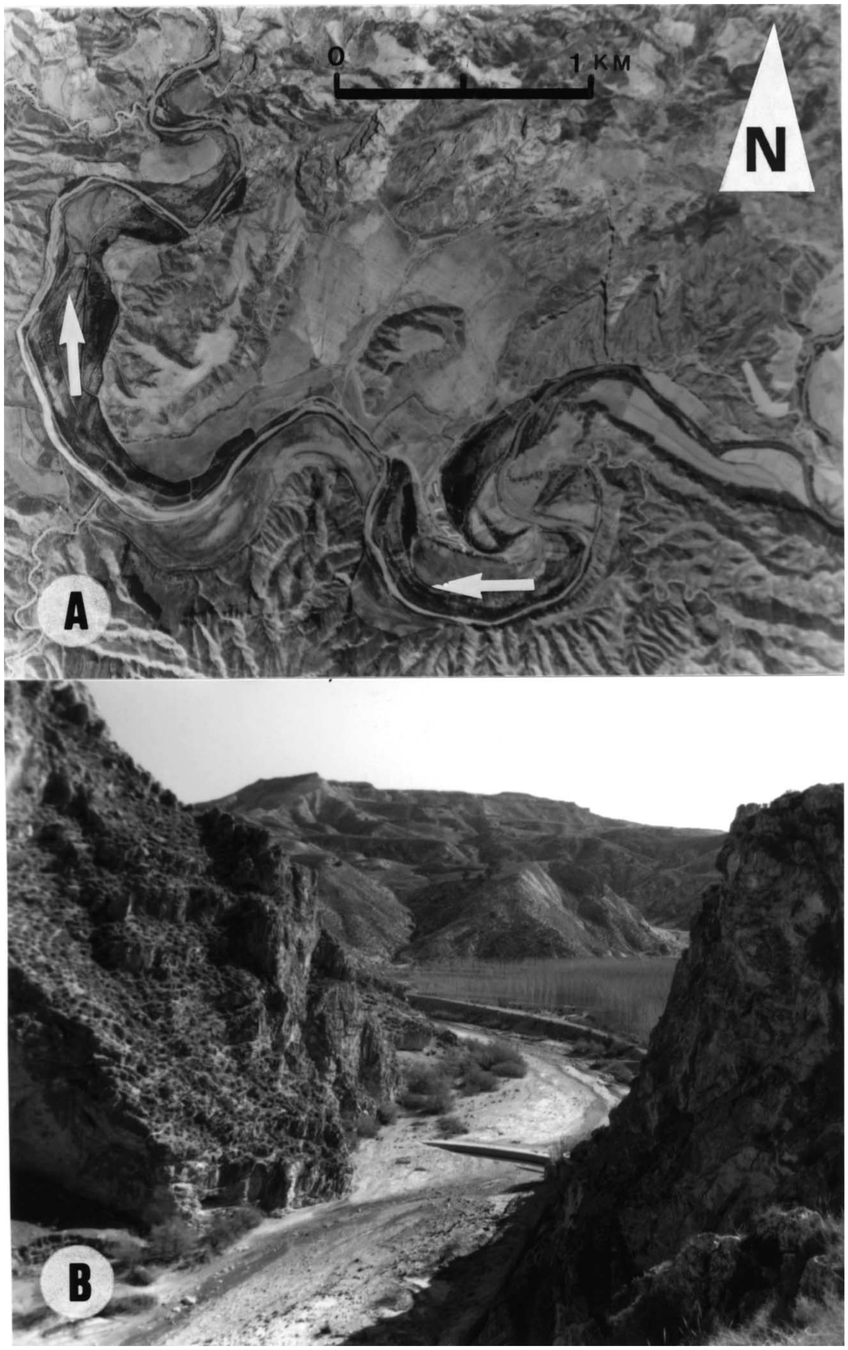

Figure 7. (A) Meandering pattern in the Guadiana Menor River as it cuts down through the basin fill into the basement. Arrows indicate flow direction. (B) Field view of a meander of the Fardes River entrenched in Jurassic limestones of the basement

streams and their ancient equivalents. Similarly, the drainage networks of the eastern and western sectors of the area are reminiscent of the characteristics of the ancient basin (centripetal drainage pattern in the eastern sector, formerly occupied by the lake, and a dendritic drainage pattern in the western sector).

However, the most central part of the region (i.e. the zone located across the two sectors) has a number of features that differentiate ancient and modern drainage and illustrate the processes involved in the inversion of the basin and capture of its drainage by part of the Guadalquivir River (cf. Vera, 1970; Viseras and Fernández, 1992).

First of all, it is noticeable that from Fonelas downstream the Fardes River appears in a more northerly position than that shown in geological maps of the ancient Axial System (Figures 2 and 8). The position of the ancient Axial System was deduced from the 1:18 000 map of Pliocene and Pleistocene palaeochannels larger than those of the transverse systems, made up of clasts and fine sediments from Sierra Nevada to the south. Moreover, palaeocurrent analysis in these channels reveals palaeoflow towards the north and northeast, which is different to the flow of the channels in the transverse systems, which also contain other lithologies in their clasts and fine sediment. Likewise, palaeocurrent analysis based on clast imbrications and sole marks (flutes and grooves) in this central part (Figure 8) shows that in the Benamaurel-Barchés reach the Guadiana Menor has a similar orientation to that of the ancient Axial System, although it flows in the opposite direction (Figure 2). Finally, there are a number of characteristic features suggesting that the drainage pattern established in the ancient Guadix Basin was captured by the basin of the Guadalquivir. The most significant features are as follows.

- In the Barchés–Chíllar reach, the Guadiana Menor flows northwards, contrary to the direction of the streams of the External Transverse System in this sector of the ancient basin (Figure 8).
- The Guadiana Menor and its tributaries in the Barchés-Chíllar reach (the Barchés, Seca, Columnas, Balata, Baúl and Guadalentín Rivers) make up a barbed drainage pattern with development of boathook bends, which are characteristic features of stream piracy. The same feature can also be recognized in the confluence of the Guadahortuna and Guadiana Menor Rivers (Barchés-Chíllar reach, Figure 8).
- The Guadalentín River flows southwards, in approximately the same direction as the streams of the ancient External Transverse System in this area (Figure 8), even though its most direct outlet to the Guadiana Menor would be at Chíllar, through the Pozo Alcón-Sancho Gómez sector.

All these features indicate that the endorheic drainage of the Pleistocene basin was captured by a tributary of the Guadalquivir, which is the Chíllar-northwards reach of the present Guadiana Menor.

DISCUSSION: TECTONIC CONTROL OF FLUVIAL CAPTURE AND ITS CONSEQUENCES

The foregoing data show that the Holocene drainage network occupying a sector to the north of Sierra Nevada has an equivalent in the drainage network responsible for the filling of the Guadix Basin during the uppermost Miocene, Pliocene and Pleistocene. This is shown by the geographical coincidence of the modern and ancient networks, by the conservation of the drainage network pattern in the eastern and western sectors of the area, and by the maintenance of straight, braided and meandering fluvial styles in the streams of the External and Internal Transverse Systems and the Axial System from the subsident stage of the basin (as inferred from architectural element analysis) until after inversion. The superimposition phenomena described in the preceding section corroborate the idea of this inheritance of the drainage pattern.

The main differences between the ancient and modern networks are found in the central part of the area, through which northward exorheic drainage now takes place. By concentrating our observations on this central part we can make some suggestions regarding the processes involved in stream capture by the Guadalquivir River of the ancient endorheic drainage of the basin.

It has been shown that, throughout the Upper Pliocene and Pleistocene, the Guadix Basin was subjected to a progressive decrease in rate of subsidence (Viseras, 1991). This is clear from mapping of isochronous palaeosol horizons whose ages are known with considerable precision as a result of numerous data on rodent palaeontology and archaeology (e.g. Agustí *et al*., 1985; Mein and Agustí, 1990; Ruiz Bustos, 1990). During the Upper Pleistocene this trend culminated in an epeirogenic uplift centring on Sierra Nevada and well described

for different locations in SE Spain (Vera, 1970; Platt, 1982; Weijermars, 1985; Viseras and Fernández, 1992; Mather, 1993; Mather and Westhead, 1993).

This uplift of the nucleus of the Betic cordillera also involved uplift of some nearby areas, such as the Guadix Basin, and had direct consequences for the drainage of the area studied here.

1. The whole basin was tilted from Sierra Nevada northwards, as shown by the northward inclination of over 20° observed in the Plio-Pleistocene fluvial sediments at numerous points near the boundary of the Internal Zone. Uplift was likewise accompanied by the appearance of a set of normal faults whose hanging walls are invariably located to the north. This accentuates the topographical differences caused by tilting in sediments of the same age located near the boundaries of the Internal Zone (more uplift) and the External Zones (less uplift).
2. The uplift with slight northward tilting (and faulting) caused modification of the profiles of the streams of the Internal Transverse System, so that in the basin they began to erode the sediments previously deposited in proximal reaches, while in distal reaches the sediments became vertically aggraded as the streams changed to an underfitting situation as regards the new profile (Figure 9). The Axial System (occupying the valley between the two transverse systems) was thus rapidly displaced northwards, and was left more elevated as regards the drainage divide between the Guadix and Guadalquivir Basins. Towards the east, in the Barchés sector, an anticlinal structure striking N65E with 5W axial plunge that had developed throughout the Pliocene and Quaternary (Estévez *et al.*, 1976) prevented this northward displacement of the Axial System (Figures 2 and 8).

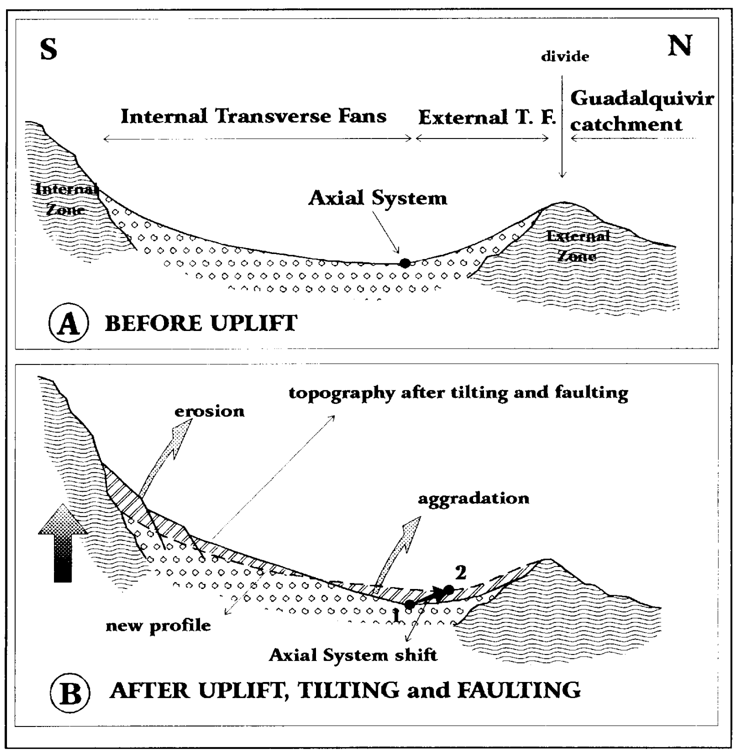

Figure 9. Modifications to the profile of the Transverse Fans and elevation and northward shift of the Axial System as a result of uplift and tilting

3. The region as a whole was uplifted in relation to the Guadalquivir Basin, which led to headward erosion by a tributary of the Guadalquivir (the present Guadiana Menor from Chíllar northwards). Moreover, the northward displacement of the Axial System to a position close to the divide between the Guadix and Guadalquivir Basins facilitated its capture by the tributary of the Guadalquivir.
4. When the Axial System was captured through the central sector of the basin, a reach of the ancient Axial System (from the mouth of the Fardes River eastwards) was probably abandoned as a beheaded stream for a short time. It is hard to determine precisely the period involved, but it must be between 100 000 and 17 000 years BP. However, the tilting caused by continuous uplift helped the beginning of westward drainage from the lake in the eastern sector, using the same route as the ancient Axial System, but in the opposite direction, as shown by palaeocurrent analysis of the sector (Figure 8). The flow would thus have been reversed in the most distal part of the Axial System, where the bed slope was very slight. Drainage from the ancient lake was thus also captured by the Guadalquivir Basin and a centripetal pattern established in its place, with general drainage towards the west.

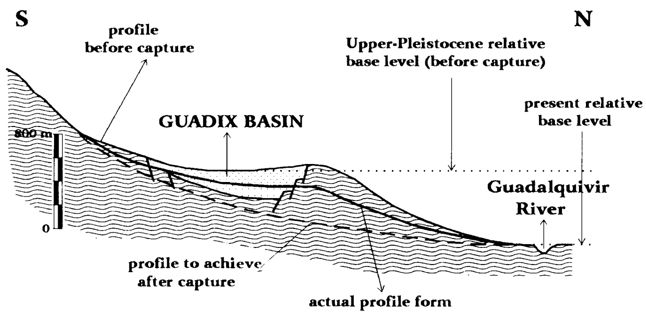

Figure 10. Pre- and post-capture profiles for the study area

Considering this combination of circumstances, after capture a new base level was established 500 m below the Upper Pleistocene (pre-inversion) base level (Figure 10). Practically the entire volume of sediments accumulated in the basin was then in a situation of disequilibrium, it was located above the new equilibrium profile. The fluvial network then began to be rapidly entrenched, at some points occupying a present position up to 300 m lower than the Pleistocene pre-inversion equivalent, taking the Pleistocene endorheic fluvial network as reference. The rapid erosion of the area was encouraged by sparse vegetation cover, low compaction and significant textural and compositional heterogeneity of the continental sediments, and by the texture of the alluvial sediments of the ancient sedimentary basin, which are easily erodible by the present-day streams.

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